NASA TN D-311

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NASA TN D-311

TECHNICAL NOTE
D-311

FULL-SCALE WIND-TUNNEL TESTS OF A SWEPT-WING AIRPLANE WITH A CASCADE-TYPE THRUST REVERSER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON April 1960

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SUMMARY

This report presents results of a full-scale wind-tunnel investigation of an F-100F airplane equipped with a cascade-type thrust reverser. The purpose of this investigation was to develop a thrust reverser satisfactory for use during the landing approach.

Longitudinal and lateral-directional stability and control data are presented for a number of reverser configurations. A reverser configuration was achieved which had only mild effects on the stability and control of the airplane, and which is believed to be satisfactory for flight research work.

INTRODUCTION

The purpose of this investigation was to develop a thrust reverser for an F-100F airplane that would provide precise flight path control during steep landing approaches (up to 16°). Previous research (refs. 1 and 2, for example) showed that thrust reverser installations on single-engine airplanes may cause large changes in stability and control characteristics, particularly when the reverser exhaust gases are near aerodynamic surfaces. However, there was not sufficient information available to allow the design of a reverser configuration which would have little or no effects on airplane stability and control. Therefore, the reverser was designed in such a manner that the exhaust flow directions and patterns could be adjusted to provide the minimum effect on the stability and control of the F-100F airplane.

This report presents longitudinal and lateral-directional stability and control data for several reverser configurations.

NOTATION

b wing span, ft

c wing chord, ft

$\bar{c}$ mean aerodynamic chord, $\frac{2}{S}\int_0^{b/2} c^2 dy$, ft

C_D drag coefficient, $\frac{\text{drag}}{q_\infty S}$

ΔC_D $C_{D_{\text{engine on}}} - C_{D_{\text{engine off}}}$

C_L lift coefficient, $\frac{\text{lift}}{q_\infty S}$

C_l rolling-moment coefficient, $\frac{\text{rolling moment}}{q_\infty bS}$

C_m pitching-moment coefficient, $\frac{\text{pitching moment}}{q_\infty S\bar{c}}$

ΔC_m $C_{m_{\text{engine on}}} - C_{m_{\text{engine off}}}$

C_n yawing-moment coefficient, $\frac{\text{yawing moment}}{q_\infty bS}$

C_Y side-force coefficient, $\frac{\text{side force}}{q_\infty S}$

F_G gross thrust from engine, lb

F_N net thrust from engine, lb

g acceleration of gravity, 32.2 ft/sec^2

N percent of engine rated rpm

p_t engine turbine discharge total pressure, inches of mercury, absolute

p_∞ free-stream static pressure, inches of mercury, absolute

q_∞ free-stream dynamic pressure, psf

S wing area, sq ft

W_e weight rate of air flow through engine, lb/sec

α angle of attack, deg

δ_D thrust reverser door position, 0 percent for full forward thrust position, 100 percent for full reverse thrust position

δ_h angle of incidence of horizontal stabilizer, deg

δ_r rudder deflection, deg

ψ angle of yaw, deg

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Subscript

u uncorrected

AIRPLANE AND APPARATUS

A drawing of the test airplane is presented in figure 1, and figure 2 is a photograph of the airplane installed in the wind tunnel.

Details of the thrust reverser are shown in figures 3(a), (b), and (c). For the installation the afterburner ordinarily used on the airplane was removed, and the jet engine tail pipe was ducted into the reverser assembly. The blocker doors at the rear end of the reverser could be set at any position from full open to full closed, thereby providing a continuous variation of thrust from full forward to full reverse. The reverser exhaust port areas were arranged symmetrically around the reverser center line, but were built so that both the locations and sizes of the port openings could be changed. The various configurations used in these tests are shown in figure 4. The reverser was also equipped with various sets of turning vanes which made it possible to adjust the direction of the exhaust gases. As indicated in figure 4, the turning vanes used for most of the tests were set at angles which progressed from 65° at the front port of the reverser to 41° at the rear port.

TESTS

The most severe operating conditions insofar as thrust reverser effects on stability and control are concerned were anticipated to occur under conditions of low flight speed and maximum reverse thrust. Therefore, it would have been desirable to make these tests at the landing-approach speed of the airplane (V_∞ = 145 knots, q_∞ = 71 psf) with the engine at military power (p_t = 56 inches of mercury, absolute) and with the reverser set in the full-reverse-thrust position. Unfortunately, limitations on both the reverser and the wind tunnel prevented operation at these conditions, and the tests were run at reduced values of engine power and free-stream velocity. However, the investigation reported in reference 1 indicated that the aerodynamic characteristics of the airplane would be the same at the reduced speeds and power settings as they would be at full-scale conditions, provided the reverse thrust coefficient, $F_G/q_\infty S$, was duplicated. For the majority of the tests the wind-tunnel air velocity was 125 knots (q_∞ = 53 psf) and the engine was set to maintain a turbine discharge pressure of 50 inches of mercury, absolute, which produced a reversed gross thrust of about 1800 pounds. These conditions provided a value of $F_G/q_\infty S$ approximately equal to that for the airplane flying at 145 knots airspeed, with military power and the reverser set for full reverse. Some tests were made at a free-stream dynamic pressure of 30 pounds per square foot and a turbine discharge pressure of 38 inches of mercury, absolute, and one run was made at a free-stream dynamic pressure of 67 psf and a turbine discharge pressure of 35 inches of mercury, absolute. The data from these tests provide additional information with which to check the validity of the scaling procedure outlined above.

The tests were made over an angle-of-attack range from 0° to 21° and over an angle-of-yaw range from -8° to +10°. Tests were also made with various stabilizer and rudder deflections to establish effects of thrust reversal on longitudinal and directional control. Some reverser configurations were tested with the reverser door at various settings between full forward and full reverse thrust. The reverser door settings are specified throughout this report in terms of percent of reverser door actuator travel. The actual door position as a function of actuator travel is shown in figure 5.

All the data presented herein were obtained with the airplane in the landing configuration (gear down and flaps deflected 45°).

CORRECTIONS

The following corrections for wind-tunnel-wall effects were made:

$$\alpha = \alpha_u + 0.803\ C_L$$

$$C_D = C_{D_u} + 0.014\ C_L{}^2$$

$$C_m = C_{m_u} + 0.0054\ C_L$$

RESULTS AND DISCUSSION

Static Thrust Characteristics

The gross thrust of the reverser as a function of engine turbine discharge pressure for various reverser door settings is shown in figure 6. It was not possible to obtain these data at truly static conditions (i.e., $V_\infty = 0$) because of excessive heating of the wind-tunnel struts and fairings by the reverser exhaust. Therefore, the gross thrust data presented in figure 6 were obtained from tests made at forward speed and have been corrected for the airplane drag and engine ram drag. The reliability of the corrections may be estimated by comparing the data shown for $q_\infty = 10$ psf with that obtained at $q_\infty = 53$ psf. While the magnitude of reverse thrust shown in figure 6 is not large, it is sufficient to accomplish the design objective of preventing air-speed increases on steep landing approaches.

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Effects of Thrust Reverser on Aerodynamic Characteristics

Basic data for the airplane with the thrust reverser installed and set for full forward thrust are presented in figures 7, 8, and 9.

The effects of reversed thrust on the longitudinal aerodynamic characteristics of the airplane are shown in figure 10 for reverser configuration r_1. A large nose-up pitching moment was found to result from thrust reversal with this configuration. It should be noted that data are shown in figure 10 for q_∞ of 67 and 53 pounds per square foot, with corresponding engine turbine discharge pressures, p_t, of 35 and 34 inches of mercury, absolute. These conditions provide approximately equal values of thrust coefficient, and the close correlation shown in figure 10 for these two sets of data indicates that full-scale conditions were closely simulated in the tests made at reduced velocities and engine powers.

The effects of reversed thrust on the lateral-directional characteristics of the airplane are shown in figure 11 for reverser configuration r_1. Examination of the plot of C_n vs. ψ indicates that a significant loss in directional stability accompanied the use of the thrust reverser.

The preceding results indicated that to eliminate the nose-up pitching moment accompanying the use of the reverser the size of the upper exhaust ports of the reverser should be decreased while that of the lower port should be increased. Since the directional stability data indicated that the reverser had a deleterious effect on the flow around the vertical fin, the upper ports were also moved downward away from the vertical fin. The resulting reverser configuration is shown in figure 4 as r_4. Operation of this reverser produced a nose-down increment to C_m of about 0.06, which indicated that the reverser geometry changes were in the right direction but too large in magnitude. The loss in directional stability which occurred with reverser r_1 did not occur with reverser r_4. Tests made with various stabilizer deflections from 0° to -25° and with rudder deflections from 0° to -15° indicated that operation of the r_4 reverser resulted in essentially no adverse effects on longitudinal or directional control.

In order to reduce the nose-down C_m obtained with reverser configuration r_4, the turning vanes in the bottom port were replaced with a set that had a higher turning angle ($\theta = 40^\circ$) that reduced the vertical thrust component. This is reverser configuration r_5 shown in figure 4. It was found that operation of this reverser produced a nose-up C_m of about 0.06, and also decreased directional stability significantly. The decrease in directional stability was quite surprising since the geometry of the upper ports was identical to that of reverser configuration r_4 which had no deleterious effect on directional stability. It is reasoned that the turning vanes with increased turning angle used in the lower exhaust port for reverser r_5 reduced the effective area of that port, with the result that the momentum of the exhaust gases from the upper ports was increased sufficiently to distort the flow over the vertical fin.

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The preceding results indicated that the changes made in going from reverser configuration r_4 to r_5 were too drastic, and therefore the original turning vanes were replaced in the lower port of the reverser, but the area of this port was decreased as shown in figure 4 for reverser configuration r_6. Data showing the effects of this reverser on the longitudinal characteristics of the airplane are presented in figures 12(a) through 12(f) for various reverser door positions. A cross-plot of these results is presented in figure 13(a) and similar data obtained with reverser r_4 are presented in figure 13(b). For reverser door settings below 90 percent the data shown for reverser r_6 are approximately the same as those shown for reverser r_4. This similarity indicates that the nose-up pitching moment increment at intermediate door settings could not be eliminated by available changes in reverser geometry, and that the best that could be hoped for was to minimize the sudden nose-down change in pitching moment which occurred when the reverser door position was increased from 90 to 100 percent.

Analysis of engine data indicated that there was a slight back pressure on the engine with all of the reverser configurations tested. It was therefore desired to test a reverser configuration having a larger exit area in the hope that the engine back pressure could be eliminated without seriously compromising the effectiveness of the reverser, or its effects on the stability and control of the airplane. The lower port was already opened to its maximum available area, so the only recourse was to increase the area of the upper ports as much as possible. The upper ports were also moved downward away from the vertical as far as possible to reduce the nose-down change in C_m which occurred for door settings greater than 90 percent, and also to keep the exhaust gases away from the vertical fin. The resulting reverser geometry is shown in figure 4 as reverser configuration r_7. Data showing the effects of this thrust reverser on the longitudinal aerodynamic characteristics of the airplane are shown in figure 14. The magnitude of the pitching-moment increments due to the thrust reverser is believed to be acceptable, at least for a research aircraft. The effects of the r_7 configuration on the lateral-directional characteristics of the airplane are presented in figure 15. Unfortunately, progressive fatigue failures of the reverser made it impossible to complete the lateral-directional tests at high engine power settings, and it was necessary to complete the evaluation at reduced power settings. The free-stream dynamic pressure was reduced a corresponding amount to give a thrust coefficient approximately equal to that used previously. These data are also shown in figure 15. Reasonably good correlation was obtained between data obtained at q_∞ of 53 and 30 psf. For yaw angles up to 4°, directional stability appeared unaffected by the thrust reverser. At higher yaw angles a loss in directional stability is indicated. However, it is believed that the indicated loss in directional stability at high angles of yaw will not seriously affect the flying qualities of the airplane.

SUMMARY OF RESULTS

The most important results of this investigation are:

1. Some of the thrust reverser configurations tested caused large changes in both longitudinal and directional stability. It was not possible to predict, either analytically or from available experimental data, a reverser configuration which would eliminate these effects, and the reverser configuration had to be modified by a trial-and-error process.

2. It was found that the pitching moment due to thrust reverser operation was strongly affected by the reverser door position. For reverser door settings up to 90 percent closed, a nose-up pitching moment accompanied reverser operation for all the configurations tested. With the reverser doors set for 100 percent reversed thrust, it was possible to alter the pitching moment due to the reverser over a wide range by variations in reverser exhaust port geometry.

3. A reverser configuration was found which produced only mild effects on stability and control and which should be satisfactory for flight research use.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Dec. 29, 1959

REFERENCES

1. Tolhurst, William H., Jr., Kelly, Mark W., and Greif, Richard K.: Full-Scale Wind-Tunnel Investigation of the Effects of a Target Type Thrust Reverser on the Low-Speed Aerodynamic Characteristics of a Single-Engine Jet Airplane. NASA TN D-72, 1959.

2. Anderson, Seth B., Cooper, George E., and Faye, Alan E.: Flight Measurements of the Effect of a Controllable Thrust Reverser on the Flight Characteristics of a Single-Engine Jet Airplane. NASA MEMO 4-26-59A, 1959.

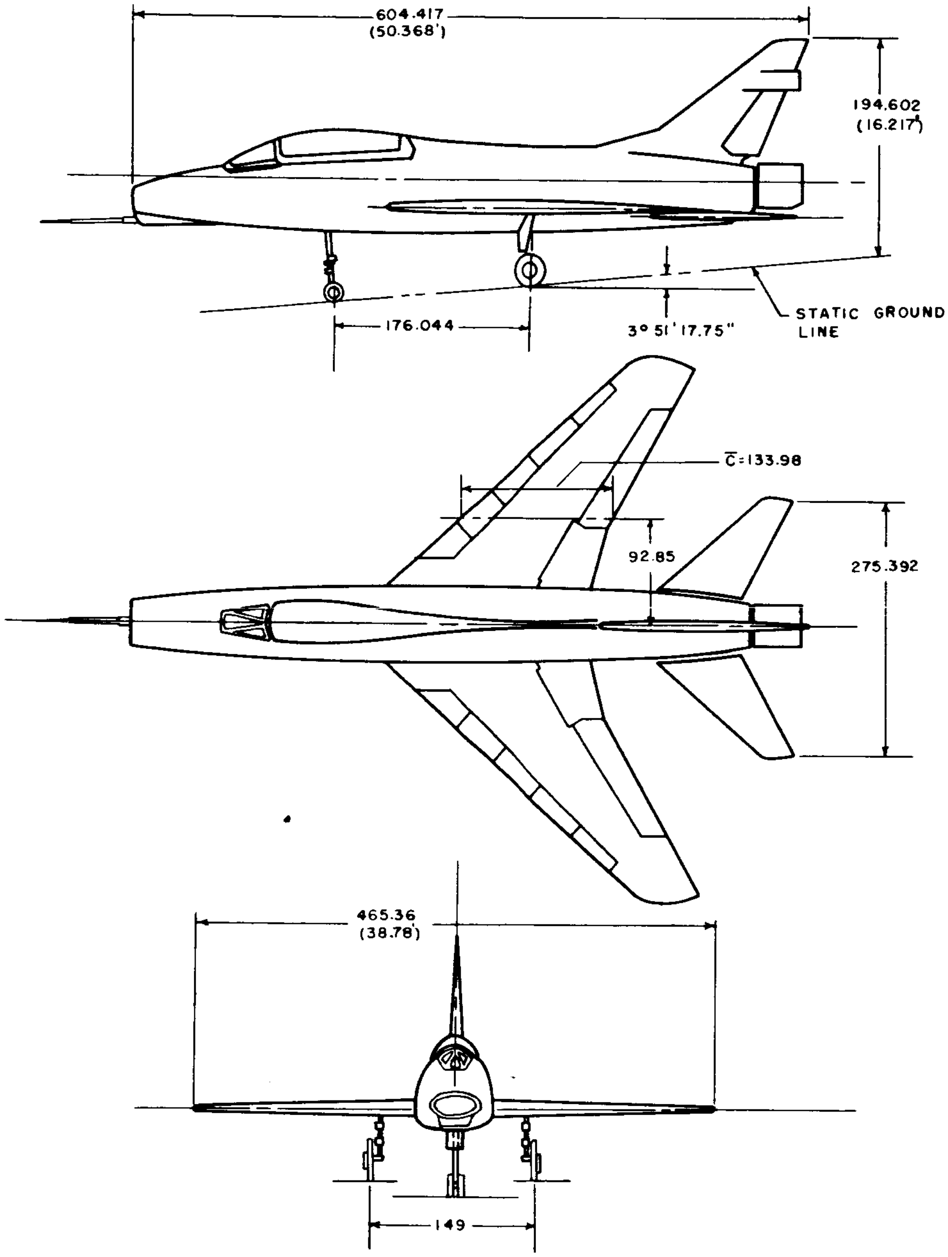

Figure 1.- General arrangement of test airplane.

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Figure 2.- Airplane installed in full-scale wind tunnel.

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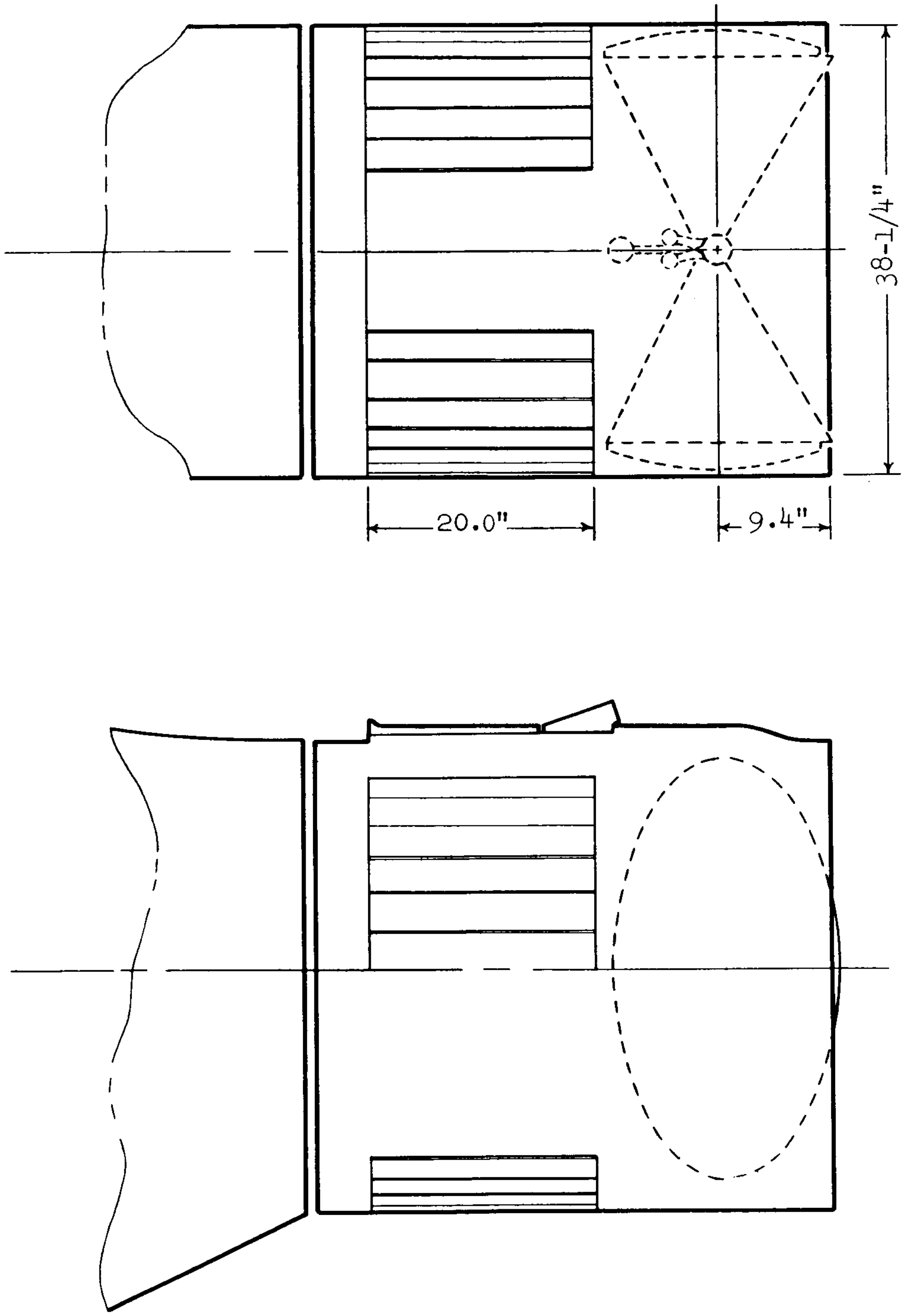
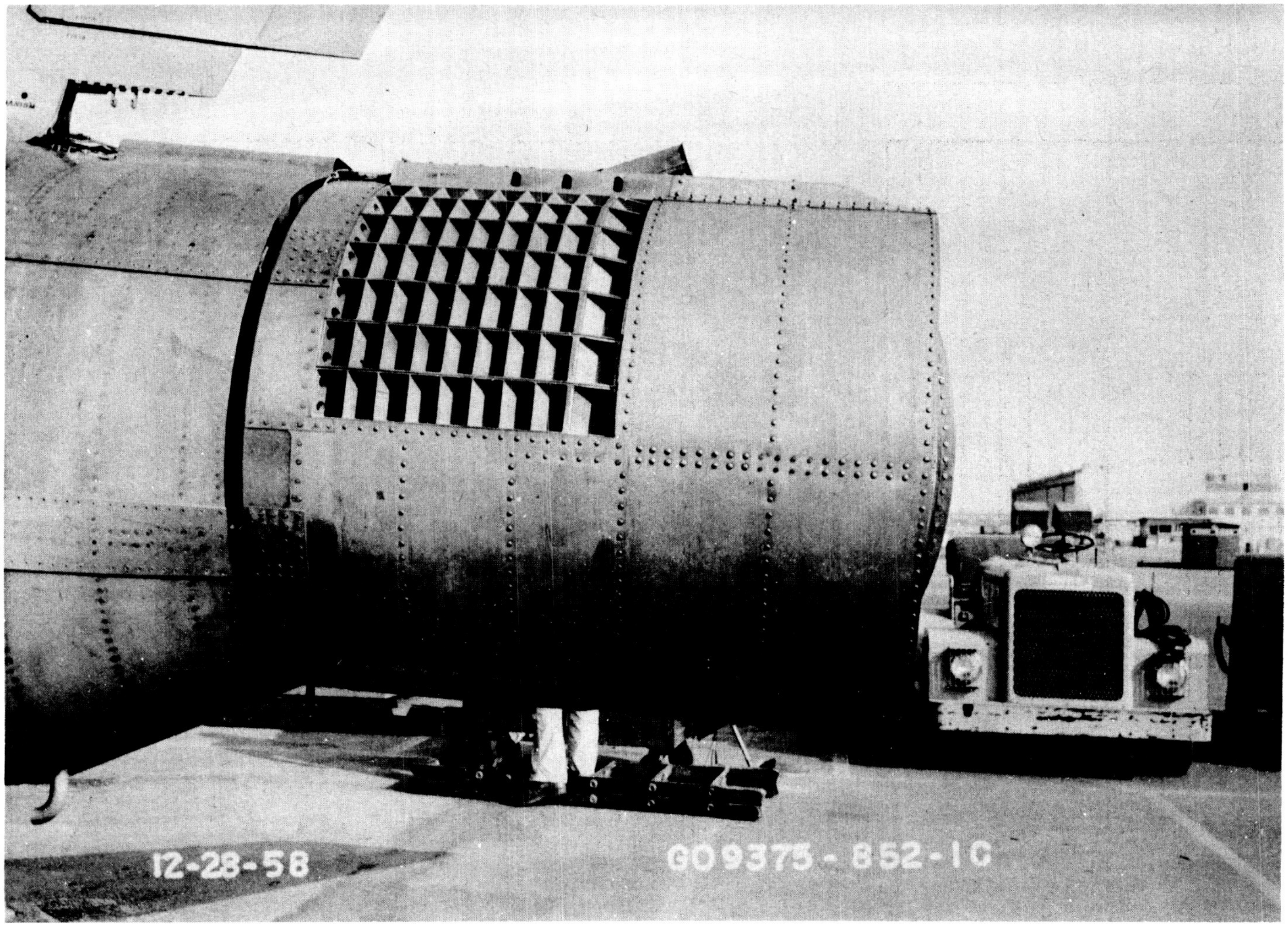


(a) Two-view drawing.

Figure 3.- Details of thrust reverser.



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(b) Side view.

Figure 3.- Continued.

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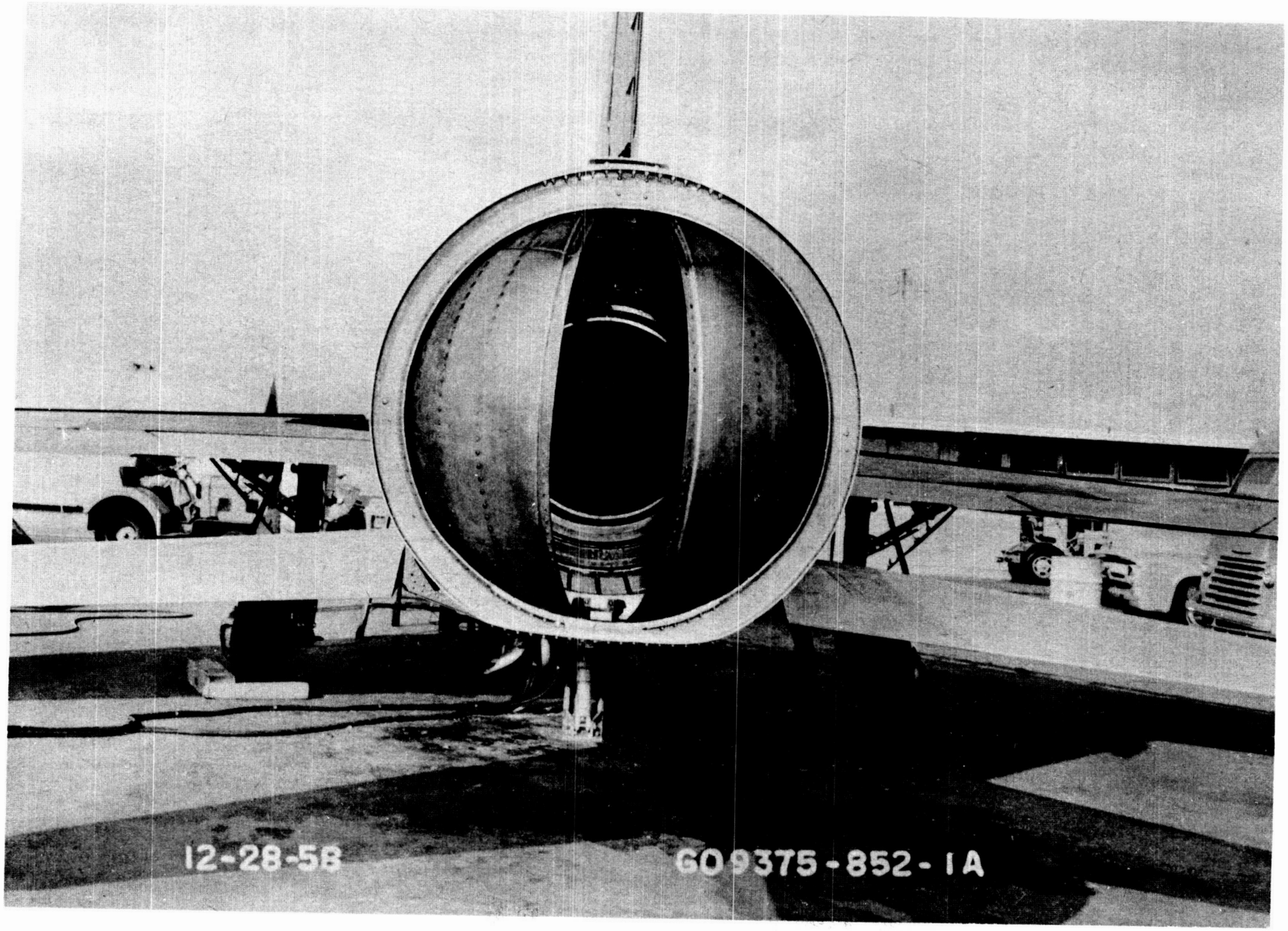

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(c) Rear view.

Figure 3.- Concluded.

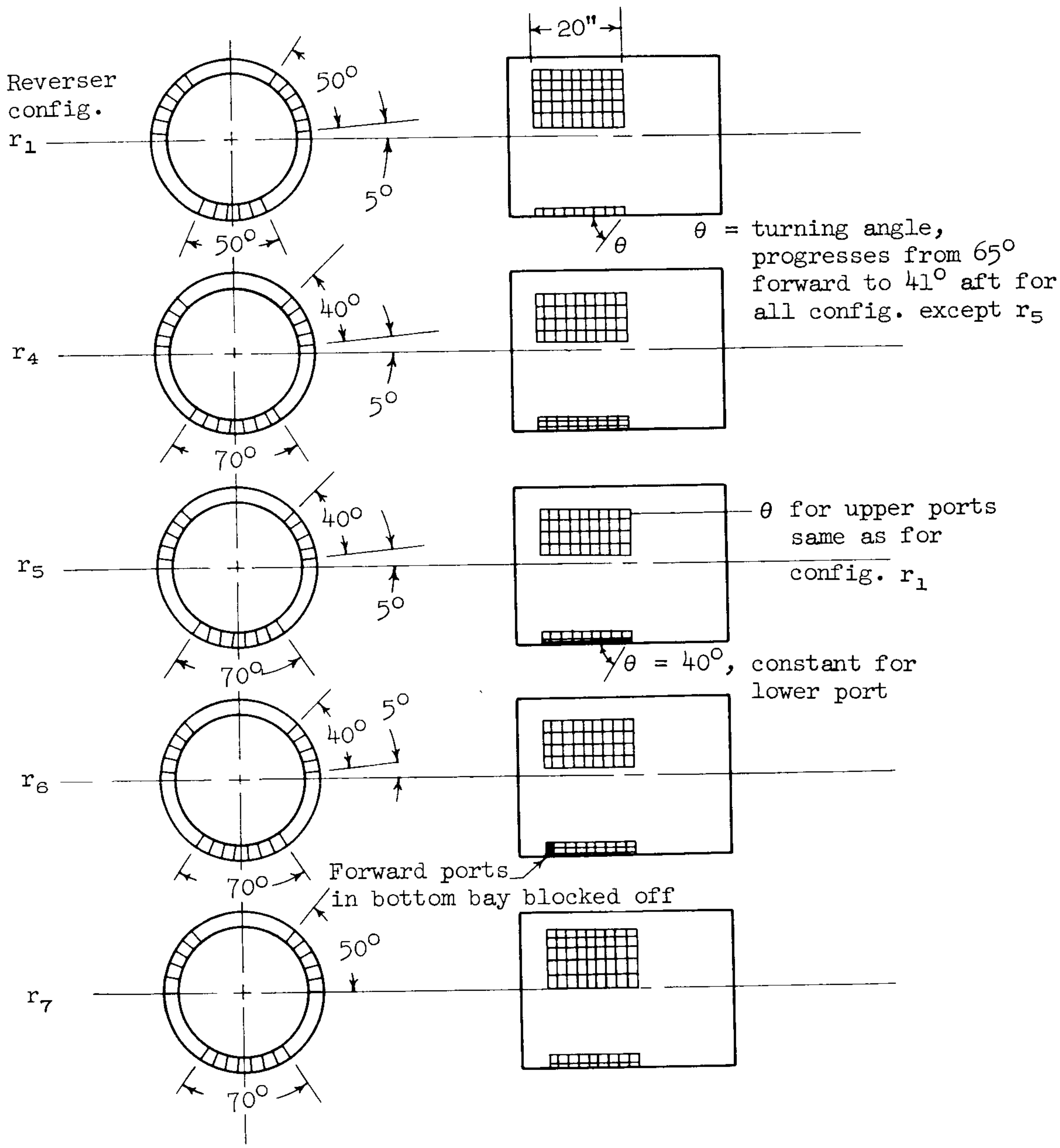

Figure 4.- Thrust reverser configurations.

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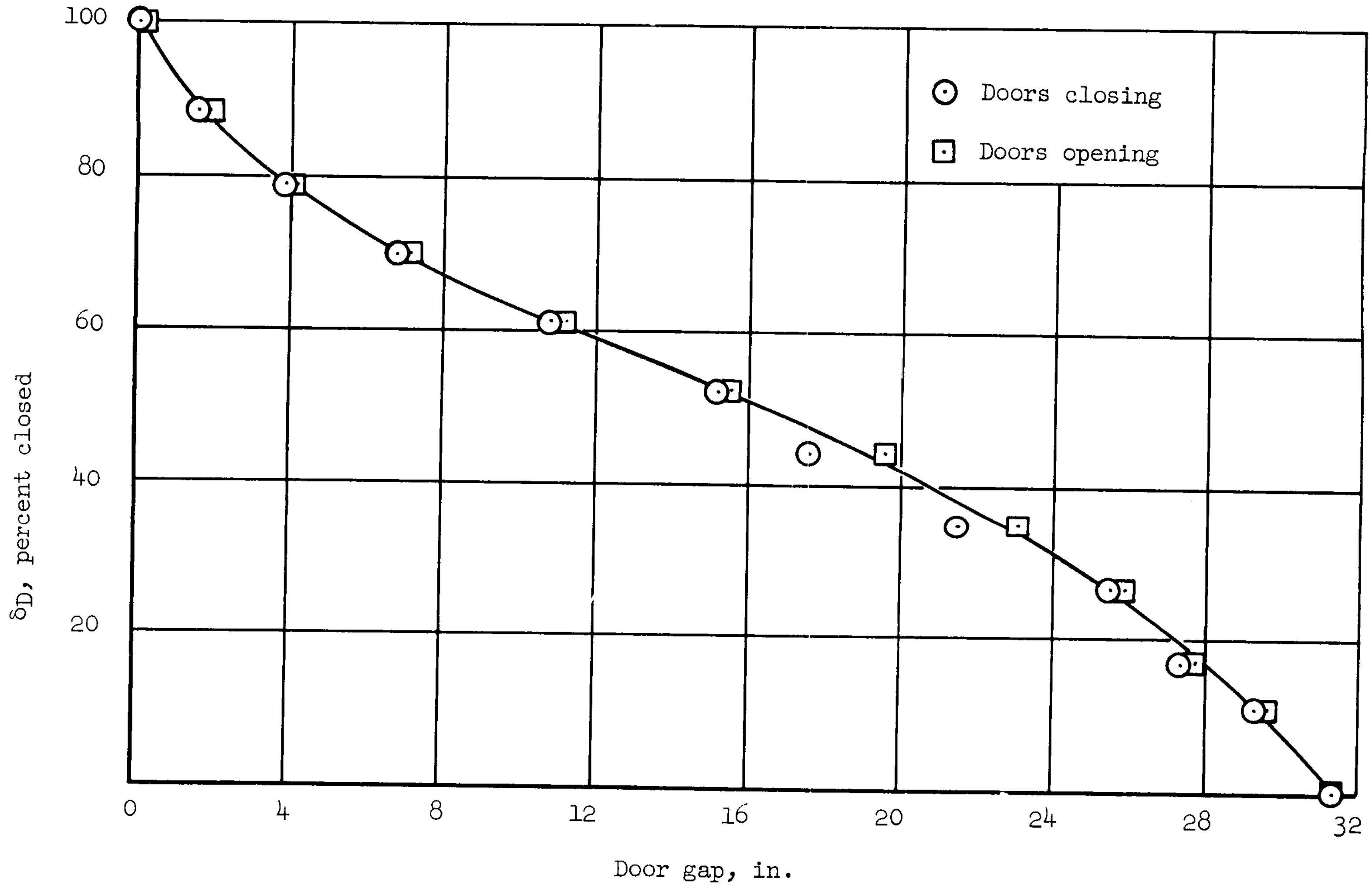

Figure 5.- Calibration of thrust reverser door position indicator.

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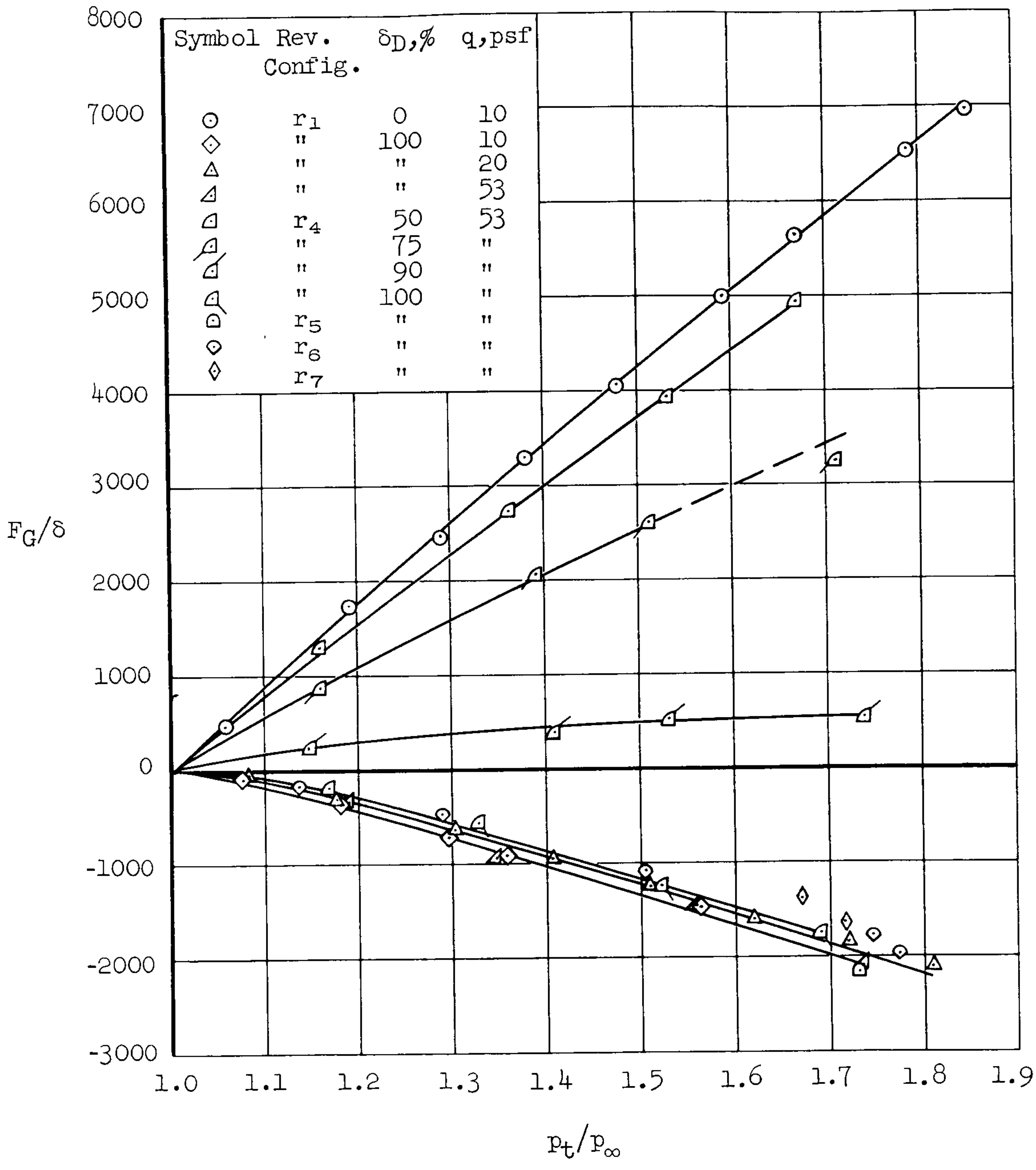

Figure 6.- Variation of corrected gross thrust with engine tail-pipe total pressure ratio and reverser door position.

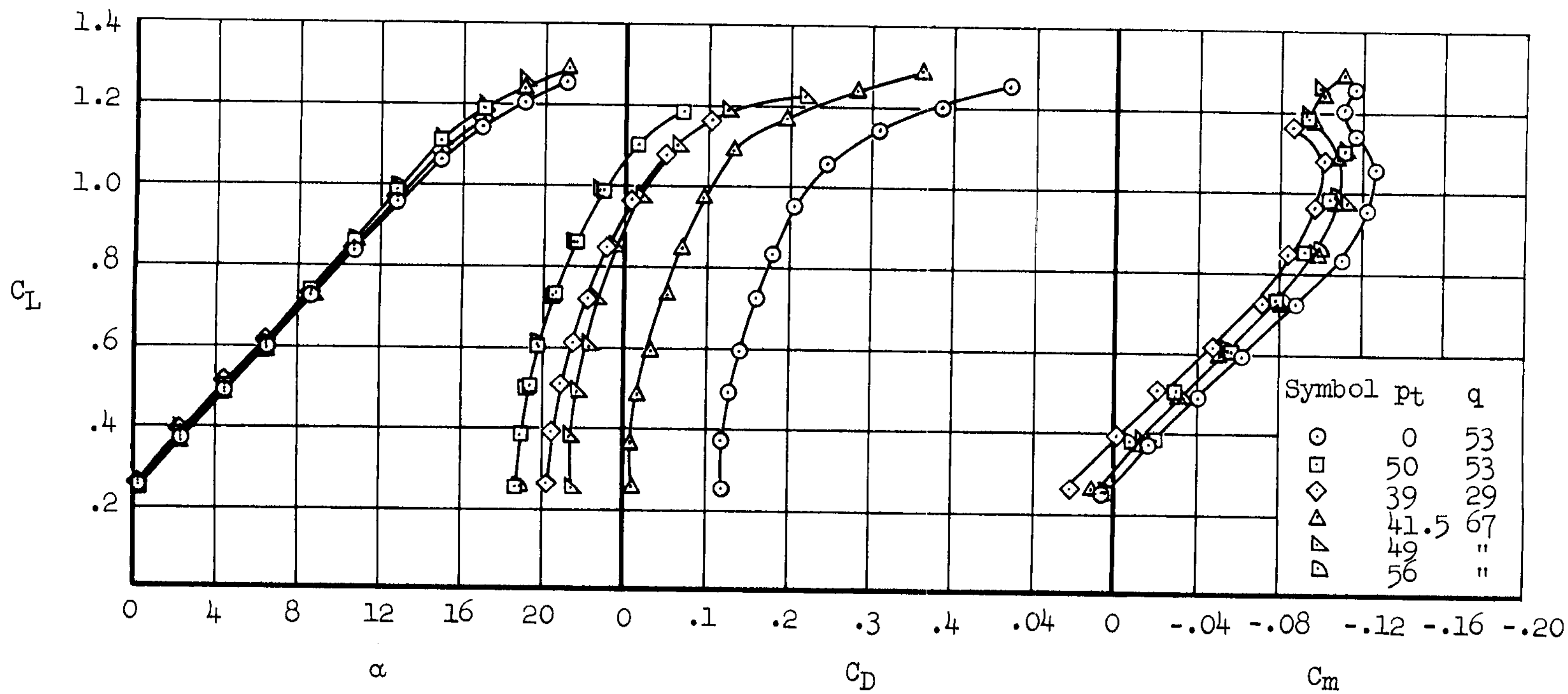

Figure 7.- Longitudinal characteristics of the basic airplane with thrust reverser installed; $\delta_D = 0$, $\delta_h = 0^o$.

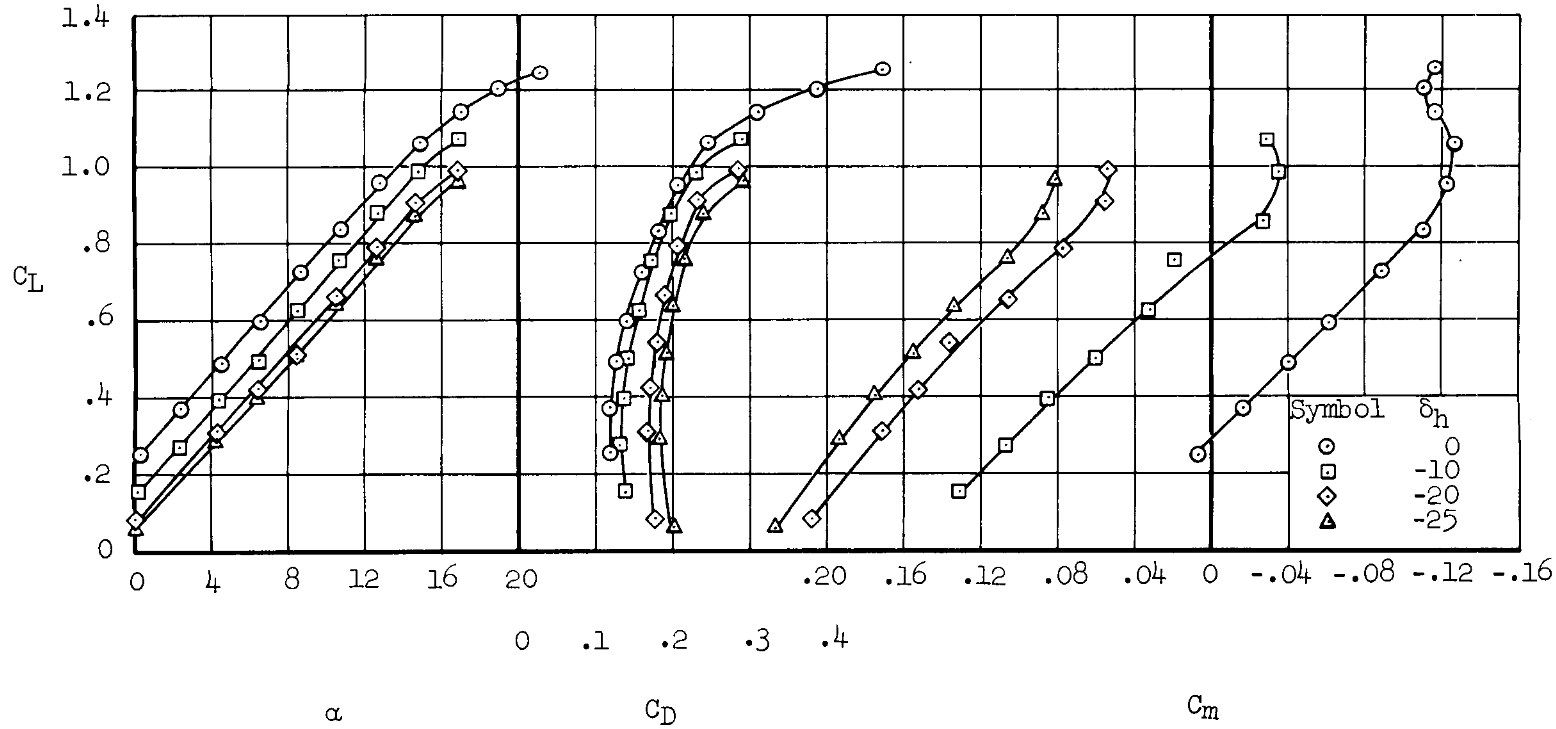

Figure 8.- Longitudinal control effectiveness; q = 53 psf, engine off.

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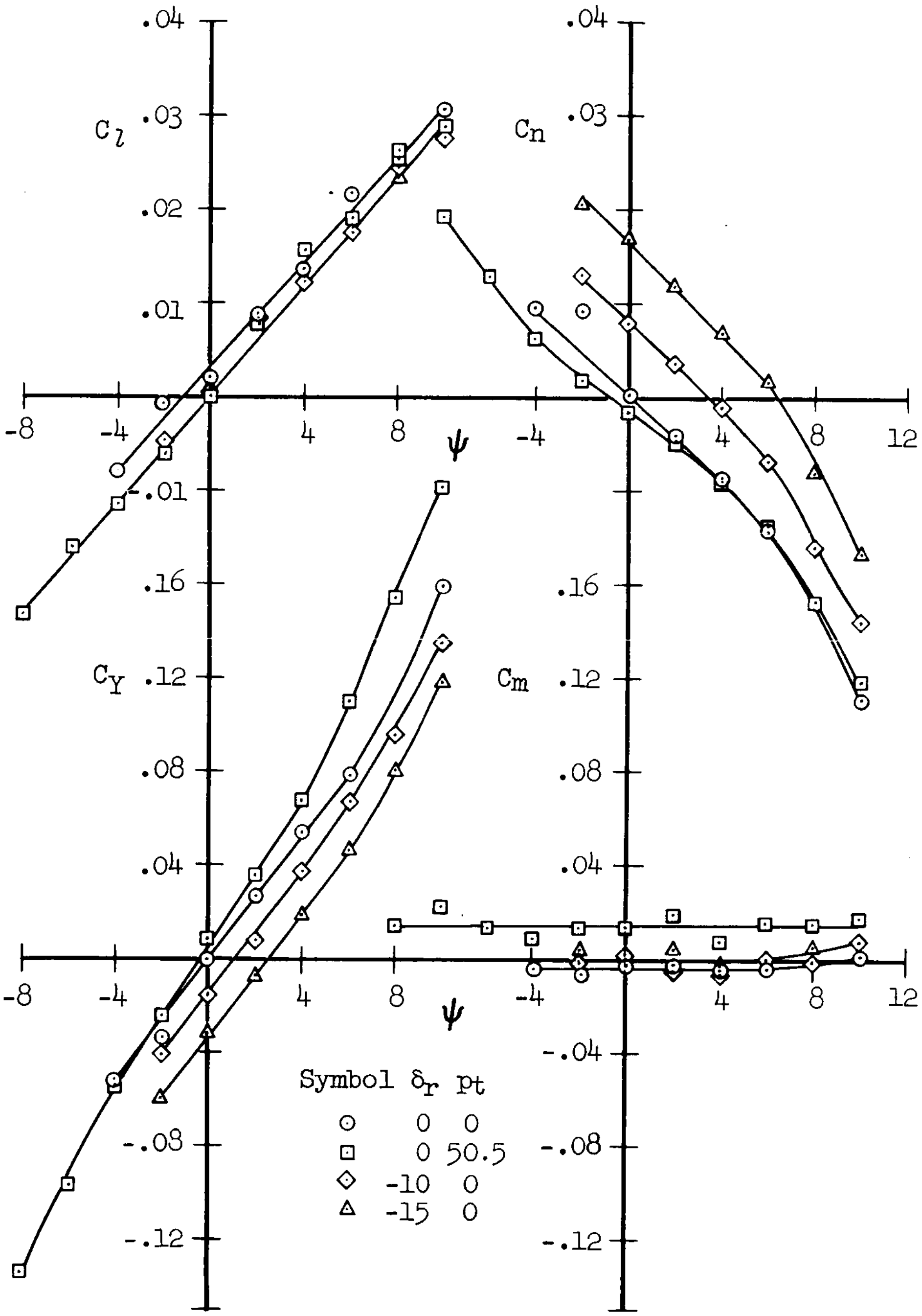

Figure 9.- Variation of C_l, C_n, C_Y, and C_m with ψ for various δ_r; $\delta_D = 0$, $q_\infty = 53$ psf.

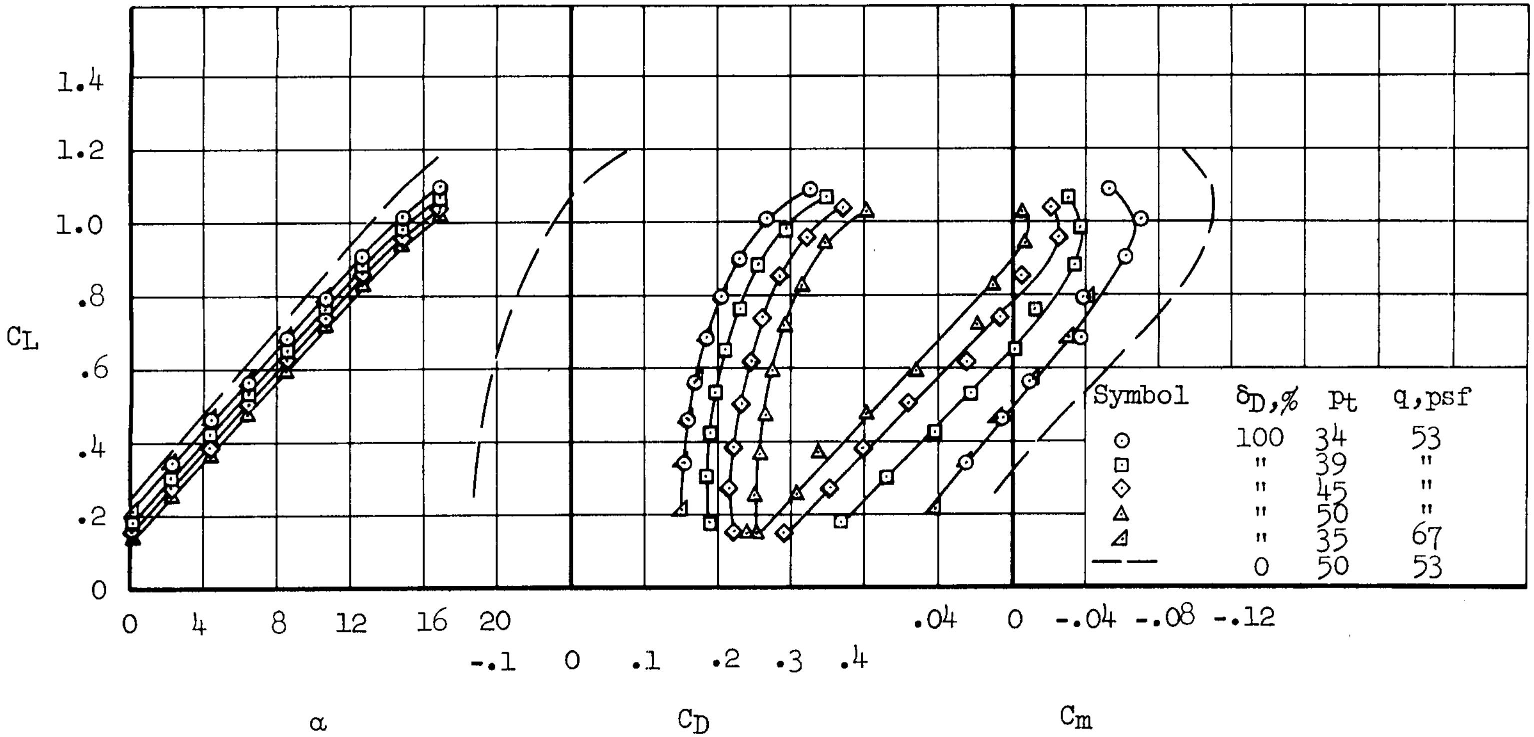

Figure 10.- Effects of thrust reverser on C_L, C_D, and C_m; reverser configuration r_1, $\delta_h = 0^{\circ}$.

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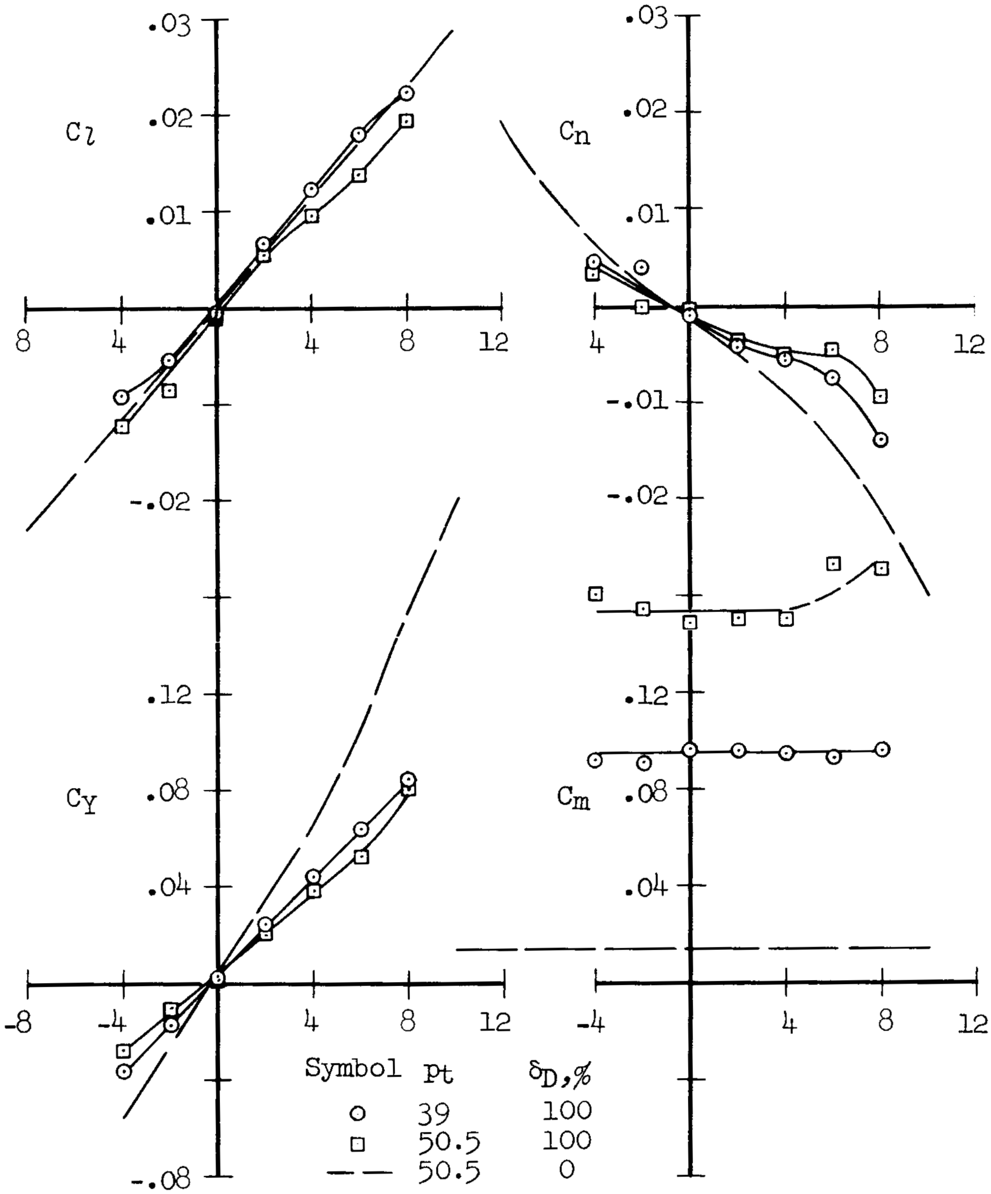
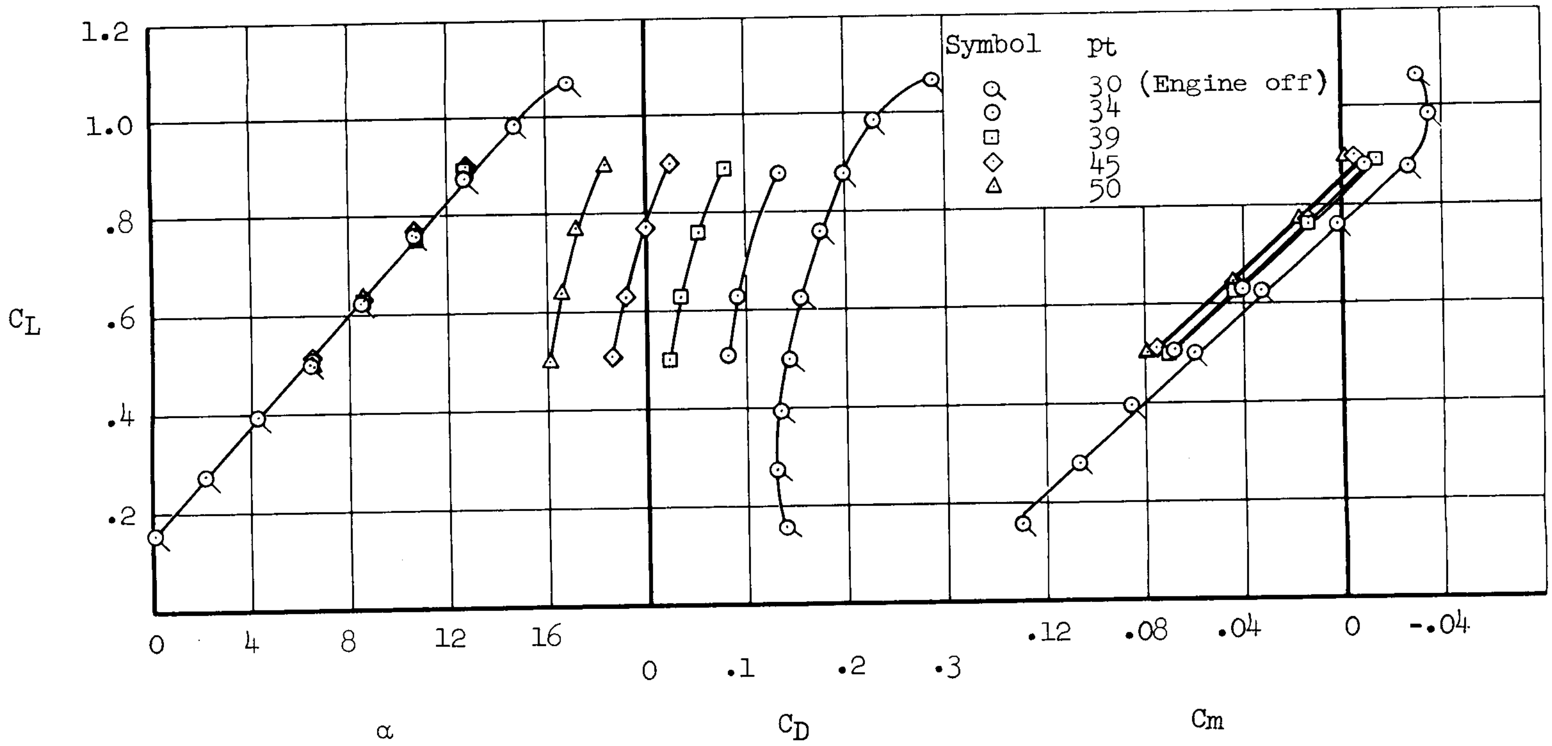


Figure 11.- Variation of C_l, C_n, C_Y, and C_m with ψ with thrust reverser operating; reverser configuration r_1, $\delta_h = -10^\circ$, $q = 53$ psf, $\alpha = 10.6^\circ$.



(a) δ_D = 25 percent.

Figure 12.- Effect of reverser door setting and power setting on longitudinal characteristics; reverser configuration r_6, $\delta_h = -10^{\circ}$, q = 53 psf.

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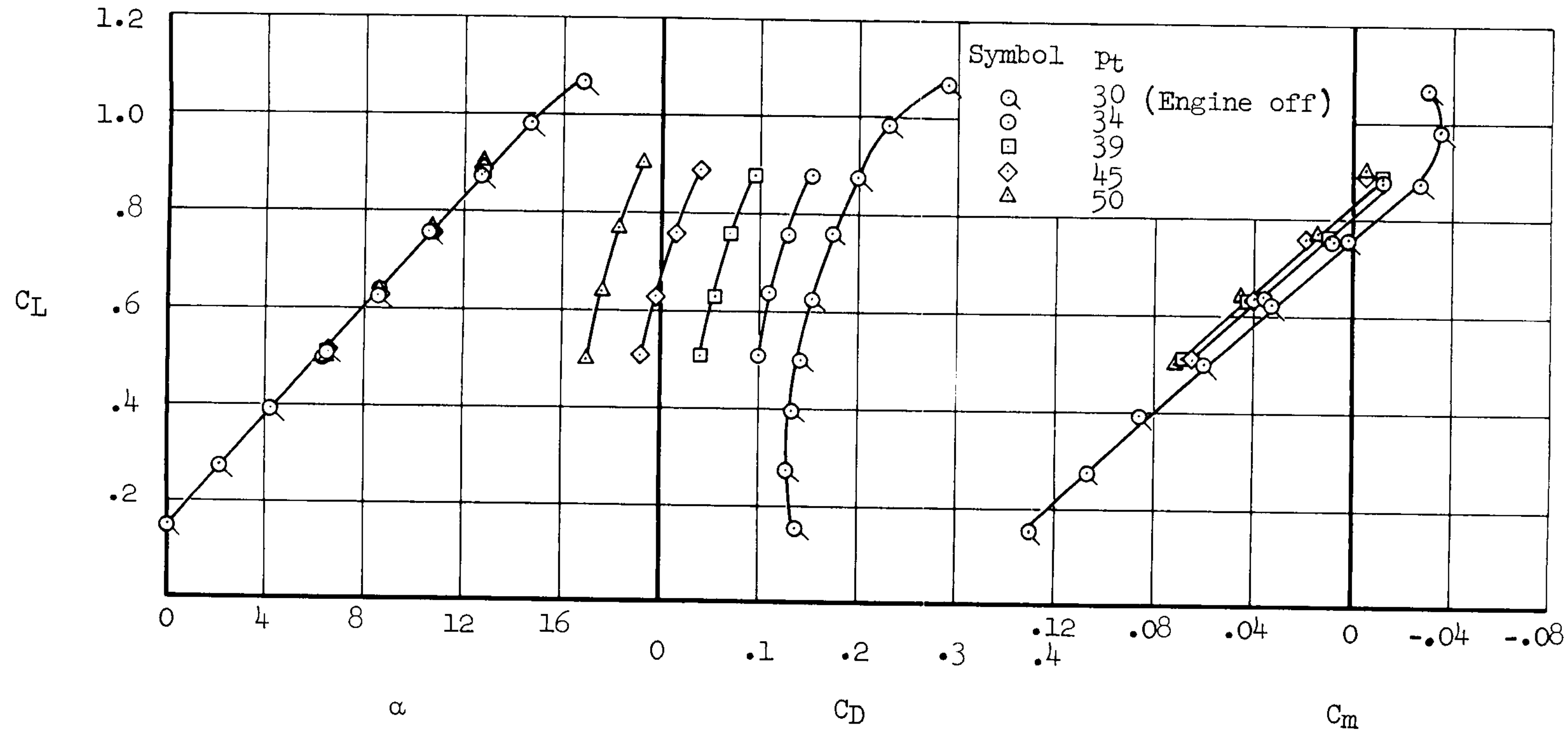
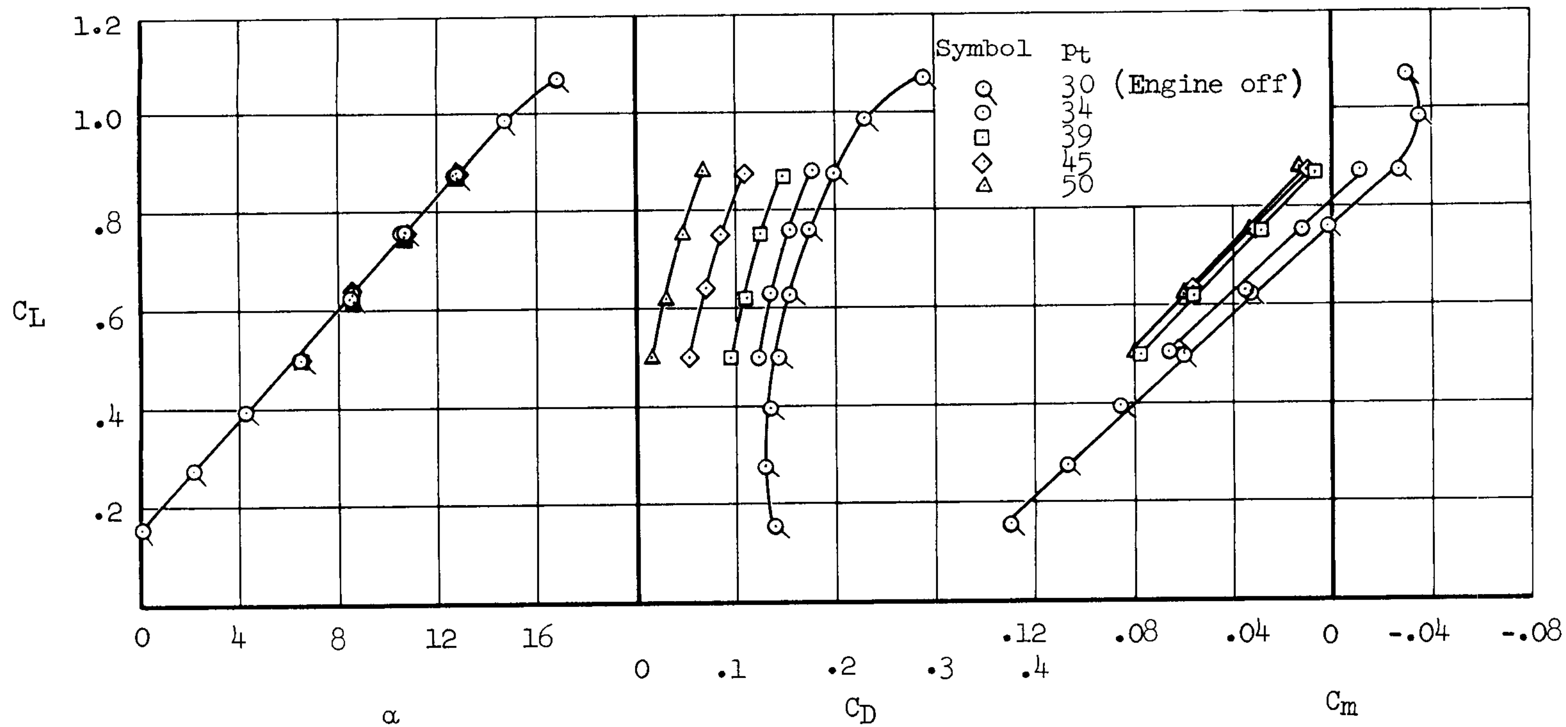


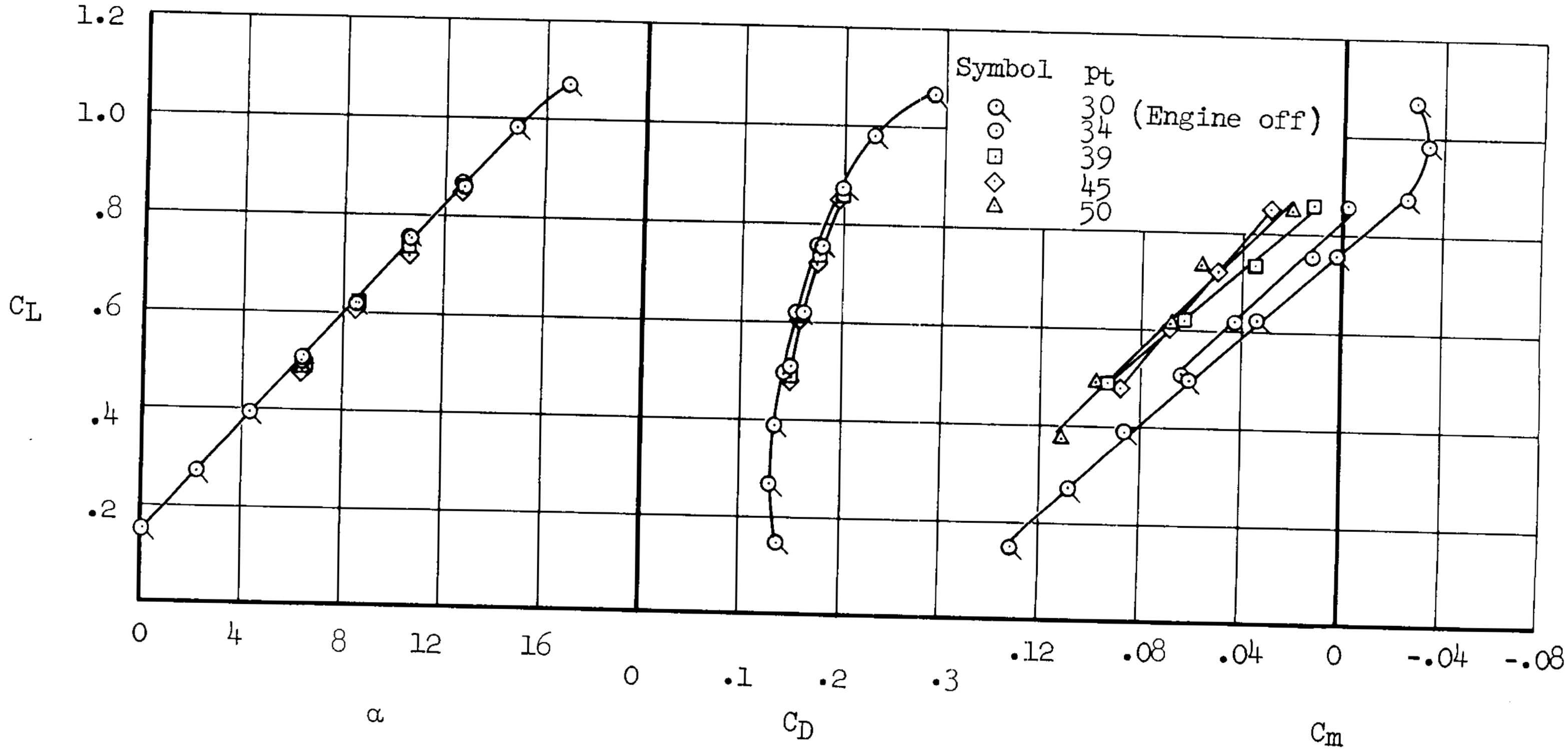
(b) δ_D = 50 percent.

Figure 12.- Continued.



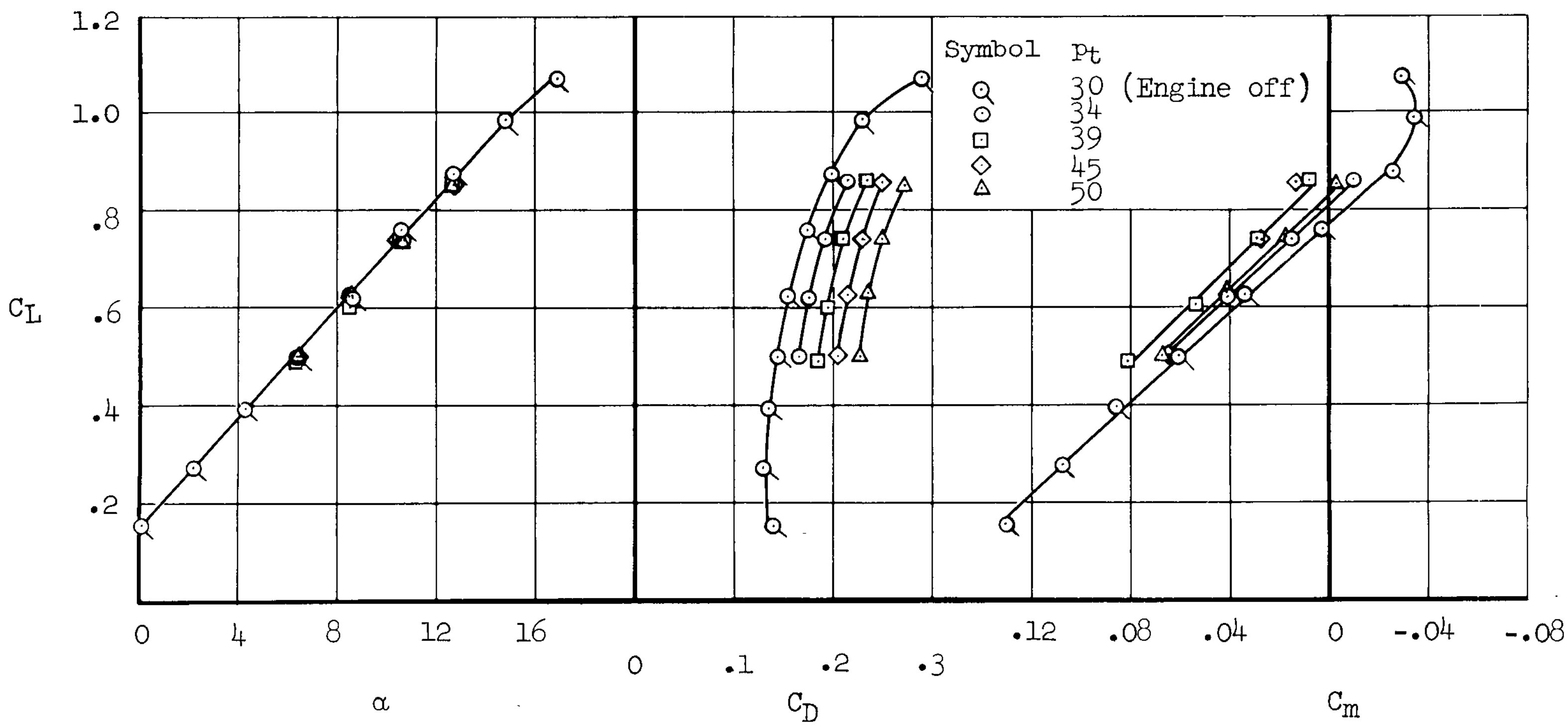
(c) δ_D = 75 percent.

Figure 12.- Continued.



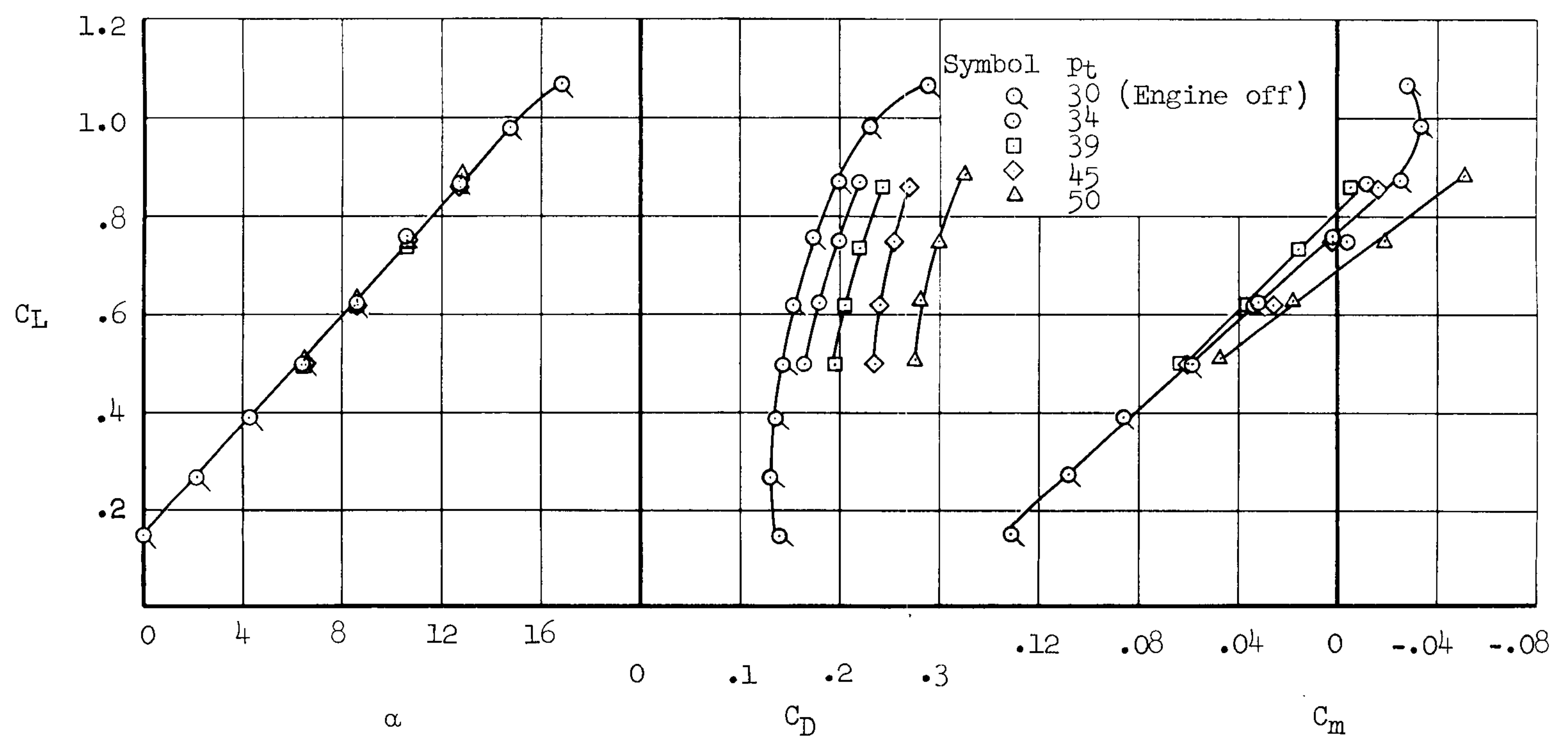
(d) δ_D = 90 percent.

Figure 12.- Continued.



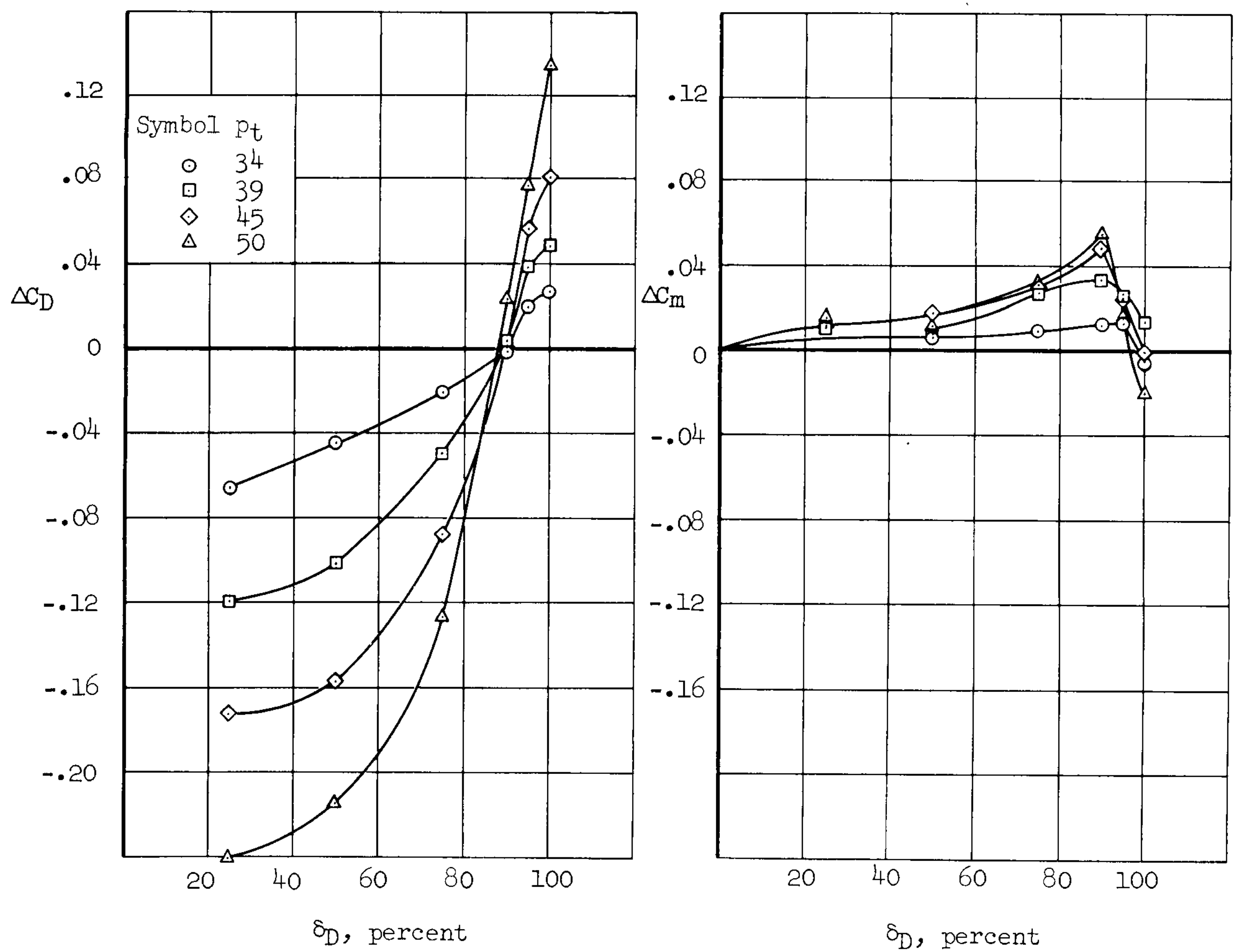
(e) δ_D = 95 percent.

Figure 12.- Continued.



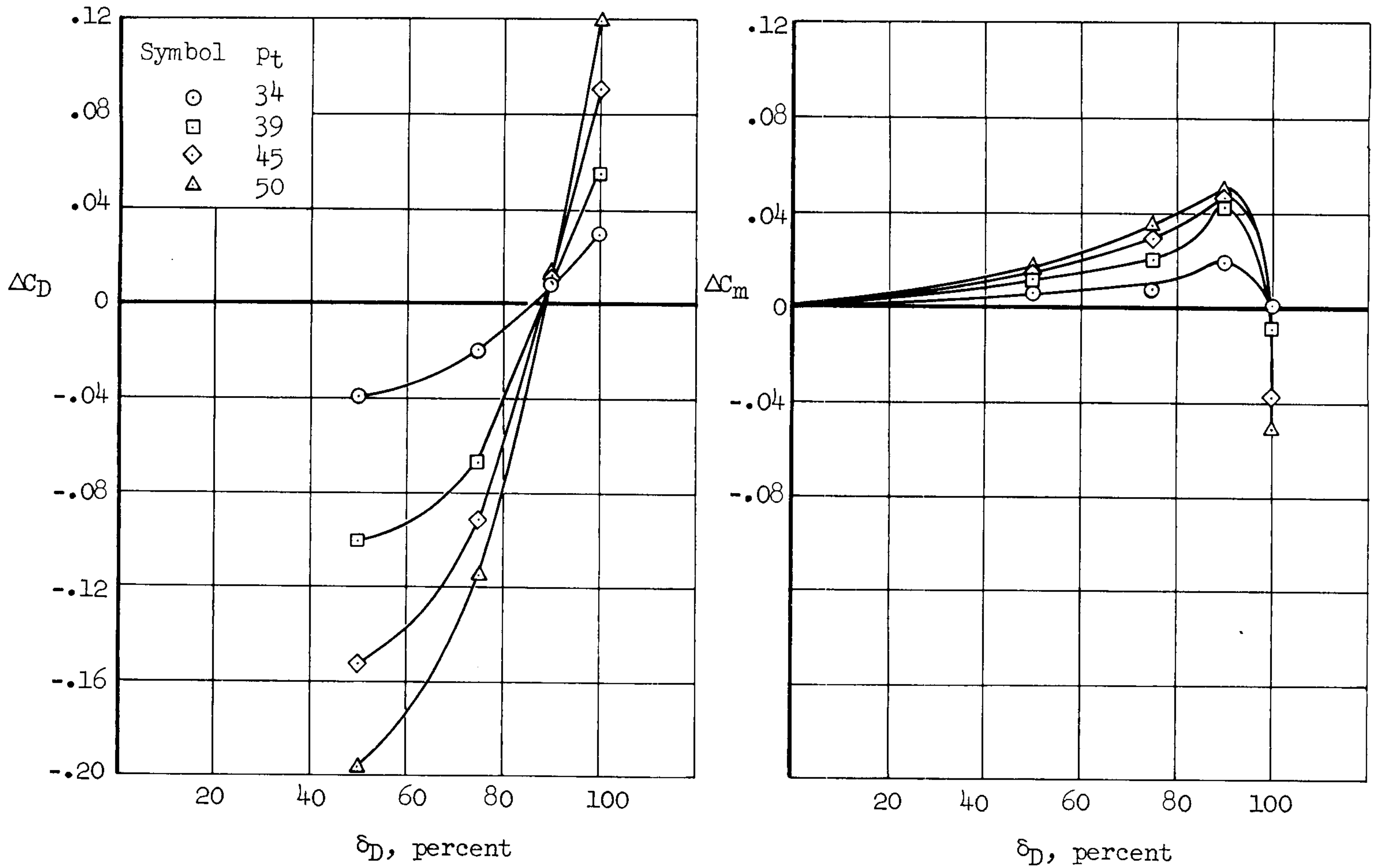
(f) δ_D = 100 percent.

Figure 12.- Concluded.



(a) Reverser configuration r_6.

Figure 13.- Variation of ΔC_D and ΔC_m due to thrust reverser with reverser door setting; $\delta_h = -10^{\circ}$, $q = 53$ psf, $\alpha = 10.6^{\circ}$.



(b) Reverser configuration r_4.

Figure 13.- Concluded.

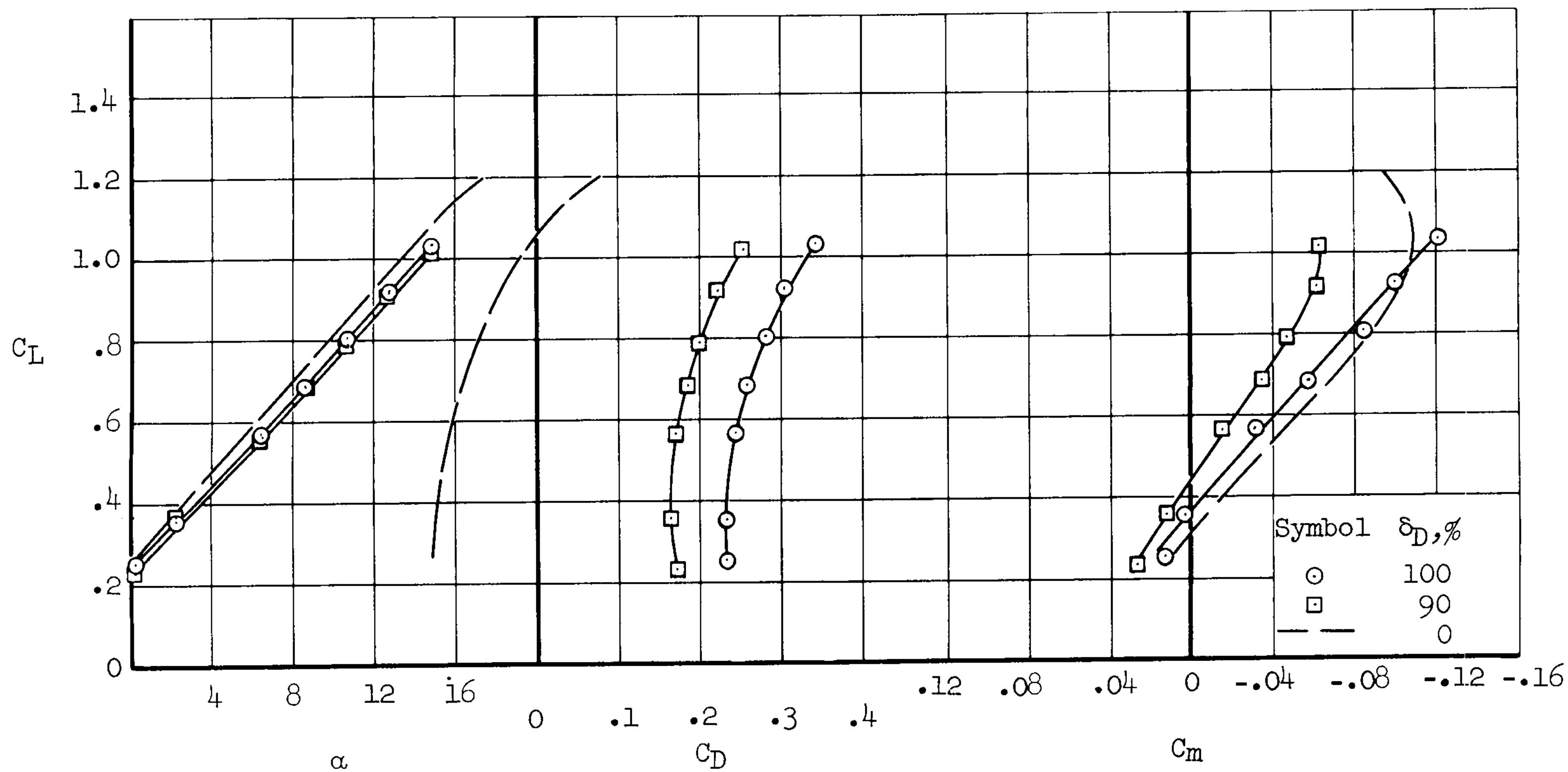


Figure 14.- Effect of reverser door setting on longitudinal characteristics; reverser configuration r_7, $\delta_h = 0^{\circ}$, $q = 53$ psf, $p_t = 50$ inches of mercury, absolute.

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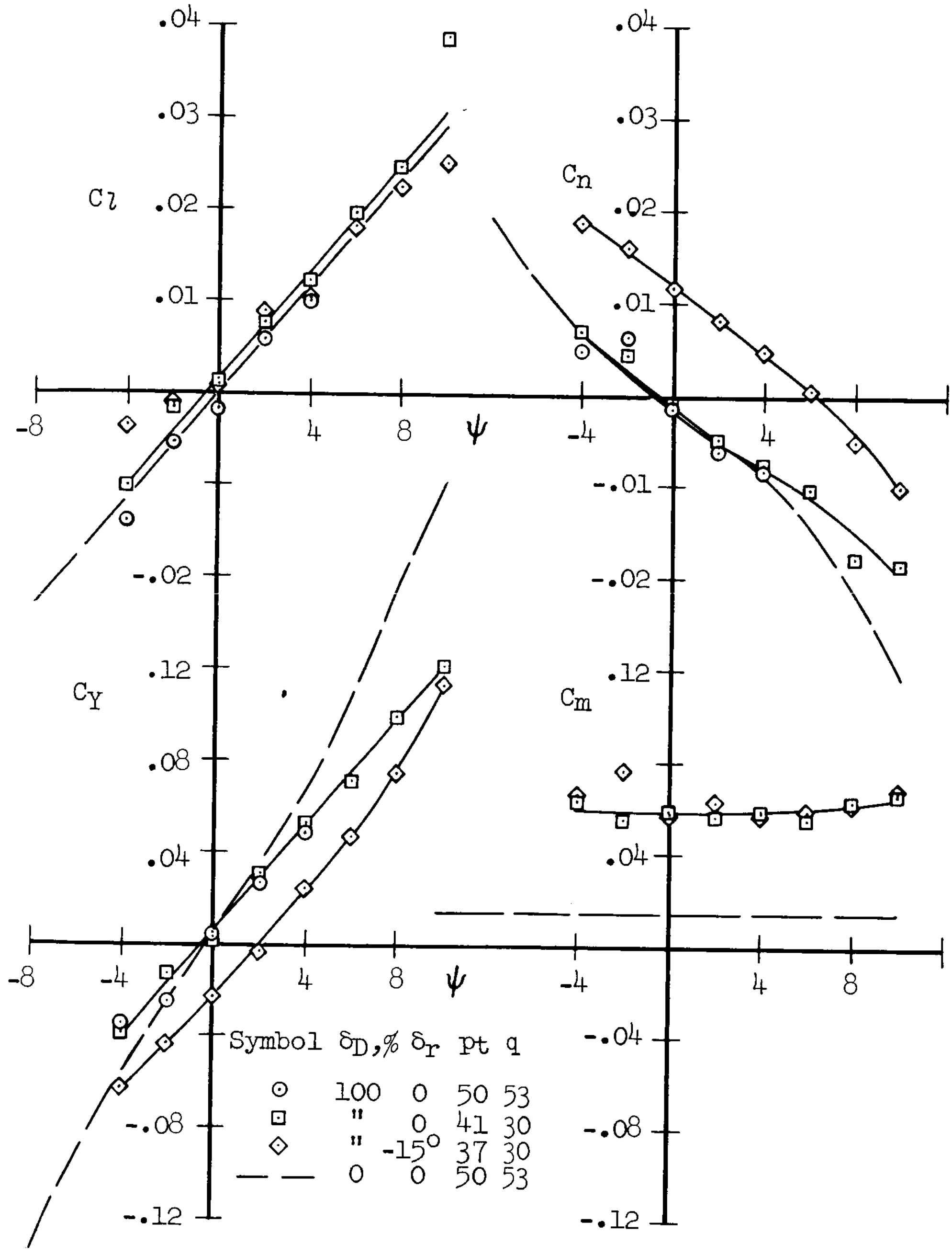

Figure 15.- Variation of C_l, C_m, C_Y, and C_n with ψ and δ_r with thrust reverser operating; reverser configuration r_7, $\delta_r = 45^\circ$, $\delta_h = -10^\circ$, $\alpha = 10.6^\circ$.